REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
10-03-2003

2. REPORT TYPE
Technical Paper

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE

Arcjet Plasma Neutralization of Hall Thrusters I: Hybrid Thruster Mission Analysis

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
William A. Hargus, John H. Schilling, Quinten E. Walker, Mark A. Cappelli

5d. PROJECT NUMBER
1011

5e. TASK NUMBER
0011

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/PRSS
1 Ara Drive
Edwards AFB, CA 93524-7013

8. PERFORMING ORGANIZATION REPORT NUMBER

AFRL-PR-ED-TP-2003-060

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/PRS
5 Pollux Drive
Edwards AFB CA 93524-7048

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S NUMBER(S)
AFRL-PR-ED-TP-2003-060

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

20030610 238

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Sheila Benner
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*
Unclassified	Unclassified	Unclassified	A		(661) 275-5963

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

FILE

MEMORANDUM FOR PRS (In-House/Contractor Publication)

FROM: PROI (STINFO) 10 Mar 2003

SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-TP-2003-060**
William A. Hargus (AFRL/PRSS); John H. Schilling (W.E. Research LLC); Quentin E. Walker and Mark A. Cappelli (Stanford Univ.), "Arcjet Plasma Neutralization of Hall Thrusters I: Hybrid Thruster Mission Analysis"

AIAA Journal of Spacecraft and Rockets **(Statement A)**
(Deadline: 28 Mar 2003)

Arcjet Plasma Neutralization of Hall Thrusters I: Hybrid Thruster Mission Analysis

William A. Hargus, Jr.
Spacecraft Propulsion Branch
Air Force Research Laboratory
Edwards Air Force Base
Edwards, CA 93524
661-275-6799
william.hargus@edwards.af.mil

John H. Schilling
W.E. Research LLC
Rosamond, CA 93560
661-275-6795
schillin@spock.usc.edu

Quentin E. Walker and Mark A. Cappelli
Thermosciences Division
Mechanical Engineering Department
Stanford University
Building 520
Stanford, CA 94309-3032
650-725-2024
650-723-2020
qwalker@stanford.edu
cap@stanford.edu

Abstract

Clustering multiple thrusters has emerged as a favored option for extending Hall effect thruster propulsion to very high powers (100–150 kW) for a variety of Air Force missions. However, there are inherent difficulties in the simultaneous neutralization of several Hall effect thrusters. Chief among these is the issue of unequal current sharing among multiple cathodes. For this reason, it may prove advantageous to use a single, high current neutralizer. Conventional Hall effect thruster neutralizers, hollow cathodes, typically consume 10% of the propellant flow and produce little or no thrust. An arcjet is an electro-thermal electric thruster with moderate efficiency and specific impulse ranges. It is also a high plasma density device that is capable of supporting and amplifying electron current through volume ionization and is capable of neutralizing single or clusters of Hall effect thrusters. By using an arcjet as a neutralizer, Hall effect thrusters will also produce useful thrust from their neutralizers. Because of the arcjet's lower specific impulse, the hybrid arcjet-Hall system will have a lower specific impulse than that of a pure Hall effect system. However by choosing suitable propellants, the hybrid Hall cluster will retain the high thrust efficiencies typical of pure Hall effect systems with the added benefit of lower total wet mass for select missions due to a higher system thrust density. This work examines the application of an arcjet-neutralized cluster of Hall effect thrusters for a low earth orbit to geosynchronous orbit transfer. The analysis shows that hybrid Hall effect clusters neutralized by a single medium power arcjet are advantageous for some orbit raising missions. Helium arcjet-neutralizers coupled with conventional xenon Hall effect anodes appear to be the superior configuration due to their relatively high efficiencies and low tankage fractions when compared to alternative propellant mixes.

Introduction

Historically, electric propulsion research has been directed at medium power technologies (500 W– 5 kW) for stationkeeping, rephasing, and orbit topping applications. Electric propulsion in this class is largely commercialized and now seeing widespread use on commercial satellites. With the commercialization of these devices, research emphasis on medium power electric propulsion will decline. The technology is of sufficient maturity, and the commercial payoffs sufficiently large, that further performance advances will be accomplished by the private sector. Therefore, the focus of Air Force electric propulsion research is being redirected toward very high and very low power regimes.

The U.S. Air Force Research Laboratory (AFRL) has initiated a program to develop Hall effect thruster (HET) systems that operate at power levels well in excess of current state-of-the-art. Program goals are for operation in the 100 kW to 150 kW range which address Air Force priorities for orbit transfer vehicles (OTVs) and rescue vehicles capable of repositioning and rescuing of marooned space assets [1]. The power range is based on that expected from proposed Air Force programs using deployed sails of thin-film solar arrays, and will adapt as predicted power availability changes. Possible solutions to achieving this higher power range include both large monolithic thrusters and clustered HET systems utilizing intermediate sized thrusters.

Clustered HET Mission Definition

AFRL has sought to define the optimal method of approaching the mission need through discussion with industry, other government agencies and universities. The study resulted in the following design criteria.

- The high-power system should use HET systems, as opposed to ion engines, due to their superior specific mass (2 kg/kW for HETs versus 8 kg/kW for ion engines).
- The high power system should be assembled from a cluster of lower power devices to reduce qualification and testing costs. A clustered system also offers the flexibility needed to meet varied power budgets on future missions. Changing the number of units in the cluster varies system power.
- The unit thruster should be a commercial flight-qualified thruster. To minimize dry mass, it should also be the highest power HET system expected to be used for geosynchronous earth orbit (GEO) station-keeping.
- An even number of thrusters should be clustered, in opposite magnetic polarity, to cancel out HET torques.

- The unit thruster power should be sufficiently low so as to allow testing in current ground test facilities. Test facility costs for a monolithic 100 kW HET could dominate program costs.

- Based on these considerations, the unit thruster power level is expected to be in the 8 kW to 10 kW range. HET units in this range are currently in development under both National Aeronautics and Space Administration (NASA) and AFRL programs.

- The individual units must be independent (i.e. no sharing of magnetic circuits or structure) so that the base units can be individually flight-qualified prior to cluster integration.

- Both the thruster and the power processing units (PPUs) should be modular to minimize qualification costs. Optimal design for the propellant management system remains an open issue.

In general, the primary advantage of a clustered approach to 100 kW-class power levels concedes performance in favor of cost. The relative advantages of each approach are summarized in Table 1.

An important consideration is the cost of qualifying a cluster versus the cost of qualifying a monolithic thruster. For each thruster to be qualified, several thousand hours of ground testing are necessary in order to qualify the thruster. As thrusters grow in size, HET scaling laws require that the background pressure of the test facilities drop as the scale length of the thruster increases. This will eventually necessitate that new, larger facilities than are currently available be constructed for ground qualification. The aim of this effort is to use the highest available powered HET system for use in clustering. This will provide the most flexibility for future Air Force and commercial missions at the lowest cost. As new thrusters of increasing power are qualified, clusters of these thrusters will be qualified and flown.

<u>Neutralization Issues</u>

With the Air Force interest in clustering of HET systems, issues involving the neutralization of more than one thruster using a single cathode-neutralizer have emerged. Cluster testing at AFRL has begun to address this issue. Tests at AFRL show that when up to four independent HET systems are operated simultaneously, each cathode will float at a unique potential. When the cathodes are tied to a common ground, this potential difference inevitably leads to a single cathode dominating neutralization. In flight, this would lead to individual cathodes sequentially overheating and subsequently failing. Obviously, the most straightforward implementation of a cluster would be to electrically isolate the various HET units and operate each independently. This would be simplest in a system where each individual HET unit is supported by a unique PPU. It is believed that spacecraft integrators would prefer to use a common PPU ground to avoid any possibility of electro-static discharge (ESD) events. One method to altogether avoid this issue would be the introduction of a single electron source to neutralize the HET cluster.

Typically, a HET expends 10% of its propellant through their hollow cathode neutralizers. Since this propellant does not pass through the cross-field ionization/acceleration region within the thruster, this propellant is not accelerated and produces little, if any, thrust. Therefore, hollow cathode neutralization produces an immediate 10% decrease in specific impulse (I_{sp}), generally before any other thruster inefficiency is considered. Researchers at Stanford University have demonstrated a novel, alternative HET configuration using an arcjet as the neutralizer [2]. Such a hybrid system can fill propulsion performance gap and provide moderate specific impulse (1,200–1,600 s) at high thrust, while maintaining high propulsion efficiency (>55%). In several experiments, it has been demonstrated that currents as high as 180% of the nominal arcjet discharge current could be drawn to neutralize a HET. These experimental results experiments have demonstrated, for the first time, that an arcjet can be used to neutralize a HET, without adversely affecting the operation of either thruster.

Although current may be thermionically drawn from an arcjet discharge, the propellant usage of an arcjet is significantly higher than that of a hollow cathode. At first glance, this would disqualify the arcjet as an efficient neutralizer. However, the use of an arcjet as a HET neutralizer opens the door to an intriguing possibility. Rather than attempt to minimize the propellant used in neutralization of the HET anode, the concept is to use a cathode-neutralizer that also efficiently produces thrust.

Since an arcjet is a high plasma density device (plasma densities of 10^{18}–10^{19} m^{-3}) that is capable of supporting and amplifying electron current through volume ionization, it is capable of neutralizing a HET cluster. For optimum cluster performance, a high efficiency arcjet is required. Helium arcjets are capable of efficiencies greater than 60% due to the absence of frozen flow losses [3-4]. Because of the arcjet's lower I_{sp}, the hybrid arcjet-HET cluster will have an overall lower I_{sp} than that of a pure HET cluster, but will produce a system with high thrust efficiency and total lower wet mass for select missions due to a substantially higher thrust density.

Mission Analysis

In order to compare the hybrid arcjet-HET thruster to conventional propulsion options, we examine a reference mission where a 2,000 kg payload traverses from low earth orbit (LEO: 400 km, 28°) to GEO (35,786 km, 0°). Such spacecraft represent the typical payload for Delta-IV class launch vehicles, using direct insertion to a geosynchronous transfer orbit (GTO) and a solid apogee kick motor to circularize in GEO. Advanced electric propulsion allows the use of a smaller and less expensive launch vehicle, such as the Atlas IIAS and Delta II Heavy (7,700 and 5,600 kg payload to LEO, respectively [5]), which delivers the spacecraft and a high I_{sp} electric OTV to LEO, and the OTV lifts the spacecraft to GEO over the course of several months. Individual HETs have been proposed for orbit raising, to reduce propellant mass and thus allow the use of these less expensive launch vehicles, but are typically associated with unattractive trip times of greater than 90 days due to their low thrust.

Model

Table 2 lists the assumptions made in this analysis. Such missions inherently require trading launch weight (and thus cost) savings against the time required to reach the operational orbit. We have therefore, determined the launch weight versus travel time curves for several of the hybrid cases described above, along with reference cases for pure HET cluster using individual hollow cathode neutralizers and chemical rockets with both storable and cryogenic propellants.

In cluster operations, it is assumed that the HET anodes are at a positive potential relative to the spacecraft chassis ground. Furthermore, the arcjet anode is kept at chassis ground, and the arcjet cathode at negative potential relative to chassis ground. The arcjet plume, absent of interactions with the HET cluster, must have a potential somewhere between that of the anode and cathode. As the HET discharge operates between the positive anode potential and ground, and the arcjet anode, cathode, and plume are everywhere at zero or negative potential relative to ground, the entire arcjet system can serve as the cathode for the HET discharge. The arcjet plume sources electrons that are drawn through space to the HET anode. The arcjet plume retains bulk neutrality by drawing electrons from the arcjet anode and cathode, with which it is in direct electrical contact. This process is shown in Fig. 1.

The detailed distribution of current flow between the arcjet anode, cathode, and plume are not well understood, but should not substantially affect the performance of a properly designed arcjet. Some current must flow directly between the arcjet anode and cathode to maintain the arc. Since the current delivered to the arcjet plume can exceed the current sunk by the arcjet cathode by up to 20%, and since some of the current sunk by the arcjet cathode comes from the arc rather than the far-field plume, there must be some current drawn directly from the plume to the arcjet anode. As the arcjet anode is grounded, this puts the potential of the arcjet plume between that of the HET plume from which it sinks current (~5V) and ground, thus small compared to the arcjet cathode voltage.

The arcjet is an electro-thermal device whose performance is driven solely by the ohmic dissipation of electric power in the constrictor region. Very little energy dissipation can come from plume-anode currents, as there is little potential difference between the two. Similarly, the cathode current will dissipate energy corresponding to nearly its full voltage regardless of whether the current source is anode or plume. So long as the cathode voltage and current remain fixed, the performance of the arcjet will not substantially change when it is used as a neutralizer for a HET.

Similarly, HET performance should remain unchanged in such an arrangement. The bulk of the acceleration occurs in the voltage drop between the HET anode and plume, and there is very little energy available at the low voltages in the plume to affect the dynamics of the thruster. So long as there is some electron source / current sink available, the performance of the HET will be driven by the known anode current and voltage.

With the two thrusters operating at nominal performance, the hybrid system can be treated as a linear combination of HET and arcjet thrusters except as follows: HET anode current can be no greater than 120% of arcjet cathode current, HET propellant flow rate is reduced by 10% due to elimination of the cathode, and HET mass is reduced by 5% due to the elimination of the cathode. If we assume that both arcjet and HET performance scale linearly, which seems reasonable for a large clustered system, the performance of a hybrid HET/arcjet cluster is as follows, where the suffixes *"HET"*, *"AJ"*, and *"TOT"* refer to values for the baseline HET, baseline arcjet, and combined system, respectively.

Power (kW):

$$P_{AJ} = P_{TOT} \frac{V_{AJ}}{V_{AJ} + 1.2V_{HET}} \qquad (1)$$

$$P_{HET} = P_{TOT} \frac{V_{HET}}{V_{AJ} + 1.2V_{HET}} \tag{2}$$

Specific Thrust (N/kW):

$$a_{TOT} = a_{AJ} \frac{P_{AJ}}{P_{TOT}} + a_{HET} \frac{P_{HET}}{P_{TOT}} = \frac{a_{AJ} V_{AJ}}{V_{AJ} + 1.2V_{HET}} + \frac{a_{HET} V_{HET}}{V_{AJ} + 1.2V_{HET}} \tag{3}$$

Specific Mass (kg/kW):

$$W_{TOT} = W_{AJ} \frac{P_{AJ}}{P_{TOT}} + 0.95W_{HET} \frac{P_{HET}}{P_{TOT}} = \frac{W_{AJ} V_{AJ}}{V_{AJ} + 1.2V_{HET}} + \frac{0.95W_{HET} V_{HET}}{V_{AJ} + 1.2V_{HET}} \tag{4}$$

Specific Impulse (s):

$$I_{SP:TOT} = \frac{V_{AJ} a_{AJ} + V_{HET} a_{HET}}{\frac{V_{AJ} a_{AJ}}{I_{SP:AJ}} + \frac{V_{HET} a_{HET}}{I_{SP:HET}}} \tag{5}$$

Where V_{AJ} and V_{HET} are the drive voltages of the arcjet and HET, respectively.

These four parameters allow linear scaling of a family of expendable OTVs using various propulsion systems – a range of HET/arcjet hybrids as considered in this study and, for comparison, conventional chemical and pure HET systems. The reference mission is the delivery of a 2,000 kg communications satellite from a 400 km, 28° LEO to GEO. This class of mission is presently performed using a heavyweight launch vehicle such as a Delta IV or Ariane 4 and a chemical upper stage. High-I_{sp} electric propulsion may allow the use of a smaller and less expensive launch vehicle, such as a Delta II, at the expense of increased trip times. However, commercial customers are resistant to trip times of more than 90 days [6]. The 5,600 kg launch mass to LEO of the relatively inexpensive Delta II launch vehicle and the 90-day acceptable trip time bound the region of greatest interest for high-I_{sp} OTVs. However, an initial mass in LEO of up to 7,650 kg would still allow the use of a mid-range Atlas II launcher and result in substantial cost savings over the present state of the art [5].

In order to characterize the various propulsion options, the trade of launch mass to 400 km, 28° LEO vs. trip time to GEO is determined for all systems. For all cases, the combined 2,000 kg payload and EOTV are delivered to a 400 km LEO by a launch vehicle, whereupon the OTV delivers the payload to GEO. The 2,000 kg payload is representative of typical high-performance communications satellites such as the BSS 702. A 400 km starting orbit was chosen to minimize the effects of solar array drag on the performance of electric propulsion systems. Purely chemical OTVs could derive a small performance benefit from using a lower parking orbit or from direct insertion into GTO; this was not considered in the present study for simplicity.

For chemical propulsion systems, the LEO-GEO transfer is made as a simple two-burn Hohmann transfer. This requires an impulsive ΔV of 4.17 km/s, and results in a travel time of less than six hours [7]. Low-thrust electric propulsion systems require a continuous-thrust spiral transfer. The ΔV required for such a transfer is given by Edelbaum's equation [8].

$$\Delta V = \left(V_1^2 + V_2^2 - 2V_1V_2\cos\left(\frac{\pi}{2}q\right)\right) \qquad (6)$$

Where V_1 and V_2 are the circular orbit velocities of the LEO parking orbit and GEO destination orbit, respectively, and q the inclination difference between the two. For a transfer from a 400 km, 28° LEO to equatorial GEO, this gives a ΔV of 5.87 km/s. The trip time is simply the time required for the propulsion system to apply the necessary ΔV, with an 88% mission-averaged duty cycle due to eclipsing.

The total launch mass to LEO (M_{LEO}) consists of the following components: payload (M_L), propellant (M_P), propellant tanks and associated structure, (M_T), propulsion system (M_R), electric power system (M_E), and miscellaneous systems such as guidance, navigation and control as well as attitude determination and control (M_S). For chemical propulsion systems, the propulsion system is assumed to be either a Pratt & Whitney RL10-A cryogenic propellant engine with a dry mass of 138.5 kg and a specific impulse of 446 seconds, or an Aerojet Transtar storable-propellant engine with dry mass 57.5 kg and specific impulse 338 seconds. Arcjet, HET, and hybrid propulsion systems are scaled linearly from the coefficients described earlier. Electric power required for these thrusters is provided by radiation hardened solar arrays with a net specific power of 40 W/kg. The tankage fraction is assumed to be 10% for all propellants except liquid helium at 15% and liquid hydrogen at 20%, due to their low density and cryogenic insulation requirements. In addition, miscellaneous systems are assumed to mass 5% of total vehicle mass.

These assumptions lead to the following relations:

$$M_L = 2000 \text{ kg} \qquad (7)$$

$$M_P = M_{LEO}\left(1 - e^{-\Delta V/gIsp}\right) \qquad (8)$$

where f_t is the average tankage fraction for the propellant mix,

$$M_T = M_{LEO}\left(1 - e^{-\Delta V/gIsp}\right) \qquad (9)$$

where t is the trip time in seconds,

$$M_R = \frac{M_P g I_{SP}}{0.88 t W_{TOT}} \qquad (10)$$

$$M_E = \frac{25 M_P g I_{SP}}{0.88 t a_{TOT}} \qquad (11)$$

$$M_S = 0.05 M_{LEO} \qquad (12)$$

and,

$$M_{LEO} = \frac{2000}{0.95 - \left(1 + f_t + \frac{g I_{SP}}{0.88 t}\left(\frac{1}{W_{TOT}} + \frac{25}{a_{TOT}}\right)\right)\left(1 - e^{-\Delta V / g I_{SP}}\right)} \qquad (13)$$

which lead to the plots of M_{LEO} versus trip time given in Figs. 2 and 3.

One further issue to be addressed is the storage of liquid helium propellant over the duration of these missions. Liquid helium is a cryogen with an extremely low heat of vaporization, leading to substantial boil-off rates. Any mission requiring substantial on-orbit storage of LHe propellant is probably infeasible, and even short-duration EOTV missions are questionable. Furthermore, the low density of liquid helium may require prohibitive storage volumes.

Examining Eqn. 13, we will find that the reference mission using the case 2 HET-arcjet hybrid will require ~1600 kg of propellant, of which ~1000 kg would be helium. This would require a storage volume of 8.3 cubic meters [9], or a 2.5 m sphere. As even a Delta II launch vehicle has a fairing diameter greater than 2.5 meters, tankage volume does not appear to be an insurmountable obstacle.

The 15% tankage fraction assumed for helium includes a provision for a multi-layer insulation scheme. With a surface area of 20 m^2, an effective emissivity of 0.002 and a surface temperature of ~200K as provided by an optical solar radiator [10], the heat conducted to the propellant will be approximately 3.6 watts. Given liquid helium's heat of vaporization of 20.7 J/g, propellant boil-off would be 0.17 g/s, giving a storage life of 68 days. Aggressive thermal design can allow for propellant storage times comparable to the missions of interest using only passive cooling, with propellant boil-off providing the necessary propellant feed.

Table 3 shows the standard HET cluster considered in this study. It consists of four SPT-140 HETs along with cathodes and power processing units [11]. Each thruster operates at a nominal power of 4.5 kW with a nominal thrust of 290 mN at an efficiency of 56%. We have chosen this HET as the baseline unit for two reasons. First, it is the highest power HET presently in an advanced state of development. As such, reliable information is available for the mass of ancillary equipment such as the PPU and propellant distribution assembly. Second, the SPT-140 is representative of several other similar HET units under development with very similar power requirements and performance characteristics.

Cases 1, 2, and 3: Hybrid HET Cluster with Helium Arcjet-Neutralizer

Table 4 shows a 2.5 kW nominal helium arcjet system with performance based on the measurements presented by Welle et al. [12]. The arcjet was scaled linearly from experimental arcjet performance data at 700 W and from commercial arcjet system mass to a proposed value of 2.5 kW necessary to neutralize the HET cluster in Table 3. The 2.5 kW helium arcjet is expected to have a discharge current of 50A. It has been demonstrated that the 1-kW helium arcjet consistently neutralize HET currents of 120% of the arcjet discharge current [2]. As would be expected, the hybrid HET cluster I_{sp} drops by 29%, but significantly, the thrust to weight and thrust to power ratios rise by 22% and 16%, respectively. The hybrid cluster I_{sp} is still above 1200 seconds with significantly increased thrust. It is important to note that this arcjet-neutralizer configuration does not represent the ideal case for a helium arcjet, but rather a linear scaling of published results to higher power levels. Case 1 therefore serves as a lower bound.

Case 1 is based on performance data measured using helium propellant in an arcjet designed for hydrogen propellant, and is therefore far from optimal. Table 4 also shows what we believe to be a reasonable extrapolation of the capabilities of an optimized helium arcjet. This improved performance thruster operates at 5.75 kW with a specific impulse of 900 s and an efficiency of 60%. The hybrid HET cluster constructed from this helium arcjet-neutralizer results in a combined I_{sp} and efficiency of 1,325 s and 53%. This is a slight improvement from Case 1 due solely to the improved performance of the helium arcjet. We feel that Case 2 is representative of the system that could be constructed if an effort was undertaken to design a helium arcjet for the express purpose of HET cluster neutralization.

Case 3, also shown in Table 4, presents the ideal performance helium arcjet for use as a neutralizer of the clustered HET system. This is based on the extrapolation of Welle et al. as the best performance that could be extracted from a helium arcjet [12]. To construct an arcjet with these performance characteristics would represent a considerable research and development effort. Therefore, Case 3 should be viewed as the upper bound, or idealized scenario.

Cases 4 and 5: Single Propellant Hybrid Clusters (Argon & Xenon)

The systems examined in the previous cases require dual propellant storage and feed systems, an undesirable complexity. We therefore consider the use of common propellants for both the cluster of Hall thrusters and the arcjet neutralizer. Table 5 presents Case 4 where we have examined the use of a xenon arcjet. As there is no experimental data available with xenon propellant, the arcjet is an estimate of performance using the relative atomic weights of xenon and helium based on the helium arcjet presented in Case 2. It assumes that the efficiency will be comparable to a helium arcjet since there will be minimal frozen flow losses and that the discharge characteristics and specific power are invariant. As expected due to the higher atomic mass of xenon (131.4 amu), the I_{sp} of a xenon arcjet is estimated at 157 s, much lower than the helium arcjets. Table 6 presents a compromise Case 5, where both the Hall thruster cluster and arcjet use argon as the propellant. In this case, the power level and I_{sp} of the HET units are kept constant. Since there is no data on the performance of the SPT-140 HET on argon propellant, the estimations of performance shown in Table 6 should only be taken as an optimistic extrapolation for this scenario. In both of these cases, the hybrid system performance is dismal. These two cases are included for completeness to show that if an arcjet neutralizer is to be used; separate propellant flow systems are required in order to produce reasonable hybrid system performance.

Cases 6, 7, and 8: Hybrid HET Cluster with Hydrogen Arcjet-Neutralizer

These three cases present the hydrogen equivalents to the helium cases and are shown in Table 7. Case 6 shows the standard HET cluster with a 6.75 kW hydrogen arcjet neutralizer. This arcjet is a scaled version of the NASA Lewis 1 kW arcjet system [12]. As would be expected, Case 1 and Case 6 have similar performance. Case 7, also shown in Table 7, presents a hybrid HET cluster with an improved performance 12 kW hydrogen arcjet. This arcjet represents the performance that could be expected from an arcjet designed explicitly for hybridization based on current technology. Table 7 also shows Case 8, which represents an optimistic upper bound of hydrogen arcjet performance.

Mission Analysis Results

The results of cases 1-3 (helium) and 6-8 (hydrogen) are shown in Figs. 2 and 3. Results from Cases 4 and 5 were not plotted due to their poor performance. In addition to the hybrid cases previously presented, three additional cases are presented as standards for comparison. These represent the chief alternatives to a hybrid HET system. The pure HET cluster is provided for comparison so that the benefits, if any, of arcjet neutralization are evident. As a check of the general principle of using electric propulsion for orbit-raising, the total LEO mass required for both storable chemical motors and cryogenic chemical engines are also provided. This study limited total LEO mass to less than 14,000 kg in order to make the comparisons in this study reasonably congruent with actual launch capabilities. Several general trends are immediately evident. In all cases, if the allowed trip time is sufficiently long, the pure HET cluster, due to its higher I_{sp}, will always be the lowest mass system. This result is only amplified by the fact that the tankage fraction for xenon storage is less than that for cryogenic helium or hydrogen. The maximum trip time examined is 120 days due to the aforementioned resistance to trip times greater than 90 days.

The higher thrust and lower tankage fraction of the helium arcjet neutralizer combine to produce a significant improvement over the pure HET cluster case for trip times less than 80 days. The pure HET case does not reduce the total mass to LEO over the nominal helium Case 2 until trip times of 83 days and with total masses 1800 kg less than the cryogenic chemical case. Meanwhile, the optimistic Case 3 has a lower mass than the pure HET case for trip times of up to 134 days. For 60-day trip times, the total mass to LEO is 2,600 kg less with Case 3 than it is with the pure Hall system. In fact at a 60-day trip time, the mass for the Case 3 mission is 460 kg less than that for the best chemical system. Even the more conservative Case 2 mission is less massive than the pure HET cluster mission by 1,470 kg at 60-day trip times. Although in this scenario, Case 2 is 680 kg more massive than the optimal cryogenic chemical case, it is 4,540 kg less massive than the storable chemical case.

The pure HET case requires a 68-day trip time to lower the necessary mass launched to LEO to the level of the cryogenic chemical case (7,950 kg). The conservative helium arcjet-neutralizer Case 1 requires a 73-day trip time to equal the LEO launch mass of the cryogenic chemical case. The more optimistic Cases 2 and 3 require 64 and 58 days. These are less than the pure HET cluster trip time. It is also interesting to note that the Atlas IIAS is capable of launching a 7,700 kg payload into LEO. This is 250 kg less than the mass at LEO required by the cryogenic chemical case. Therefore, an Atlas IIAS vehicle cannot currently launch the model mission with even the most capable LEO to GEO chemical transfer stage.

Using the maximum rated launch capability of the Atlas IIAS, the pure HET cluster would deliver the model spacecraft to GEO in 70 days. Our conservative Case 1 would deliver the same payload to GEO in 75 days. Cases 2 and 3 would deliver the payload in 66 and 59 days, respectively. Down selecting to an Atlas IIAS from a larger vehicle would result in significant launch cost saving. Ideally, industry would prefer to reduce costs by further down selecting to less expensive vehicle such as the highly reliable Boeing Delta II while maintaining a payload mass of 2,000 kg and a trip time of less than 90 days. Cases 2 and 3 fulfill these requirements by reducing the mass boosted to LEO to less that the 5,600 kg capability of the Delta II Heavy.

Although the hydrogen Cases 6-8 have higher specific impulses than the corresponding helium Cases 1-3, the nominal hydrogen Case 6 does not significantly improve over the pure HET cluster case over any portion of the range of trip times. In fact, the nominal hydrogen case generally has higher total LEO mass. Even the optimal, very optimistic, Case 8 only shows reduced total LEO mass for trip times of less than 103 days. At 60 day trip times, this case reduces total LEO mass by 995 kg over the pure HET case; although, it should be remembered that at the mass for both these cases is at least 1,150 kg greater than the cryogenic chemical case. In order to match the cryogenic chemical case, the pure HET case requires 68 days, while Case 8 requires 65. Of course for this trip time, the nominal Case 6 is 225 kg more massive than the pure HET case. Overall, the use of hydrogen arcjets to neutralize a HET cluster provides little, or no, advantage of the pure HET, or the helium hybrid HET systems.

It is evident that the ideal HET hybrid system will require the use of a helium arcjet. This restricts the system to short term missions (less than 120 days) due to the issues associated with the on-orbit storage of liquid helium. Hybrid HET-arcjet systems are therefore of limited use for general orbit maneuvering due to the storage requirements of liquid helium. However, a niche for initial high ΔV missions exists for this technology as is shown in this mission analysis.

Conclusions

The results presented here provide support for the development of helium arcjet sources as neutralizing cathodes for high power HET clusters. The neutralization of a HET with an arcjet plume creates a moderate thrust, moderate specific impulse electric propulsion thruster package that can fill a performance niche that is not currently filled.

We have examined various cases of a hybrid HET clusters with arcjet neutralization. Three broad classes of HET clusters with arcjet-neutralizers were examined; helium, hydrogen, and single propellant systems. From these it was determined that in order to maintain reasonable performance characteristics, the arcjet and HET cluster would each require a separate propellant system. Examination of the two most promising arcjet concepts (helium and hydrogen), illustrated that the higher propellant density and system thrust to weight ratio of the helium arcjet overcomes the higher specific impulse of the hydrogen arcjet for the sample LEO to GEO transfer mission.

Hybrid HET clusters using arcjet-neutralizers have several limitations. One serious drawback is the requirement of two propellant management systems due to the differing propellant properties required of HET and arcjet thrusters. Lifetimes of hollow cathode neutralizers has been measured to over 20,000 hours and the lifetimes of HETs such as the SPT-140 referenced in this study are an estimated to be approximately 7,000 hours. This compares to arcjets with lifetimes of 3,000 hours or less. The model mission lengths of interest are only approximately 2,200 hours. So arcjet lifetime would limit use of this concept to single use missions. Another limitation is the storage issues associated with cryogenic helium, which restrictions mission duration.

Alternatively, the lifetime of SPT-140 HET units limit the use of an electric OTV to two round trips. The placement of one or two spare arcjet-neutralizers would provide sufficient neutralization for the expected life of the HET cluster. The higher density of the arcjet-neutralizer plume will provide increased electron conductivity in the near plume region of the HET cluster and for this reason may be a preferred neutralization method not only for HET clusters, but also for very large individual thrusters. Within the restriction of operation to early in a mission timeline, hybrid HET-arcjet systems appear capable of putting larger payloads on station within 60 days than either pure HET systems or chemical upper stages. This may provide increased mission capability at lower cost for users with large payloads.

Acknowledgements

The Air Force Office of Scientific Research supported the work at Stanford University.

References

1. *1998 Strategic Master Plan,* Air Force Space Command, Department of the Air Force, 1998.

2. Q. E. Walker, N. Gascon, M. A. Cappelli, W. A. Hargus, and J. A. Schilling, "Arcjet Plasma Neutralization of Hall Thrusters: Hybrid Thruster Proof-of-Concept Demonstration," submitted to the *AIAA Journal of Spacecraft and Rockets* for publication.

3. Q. E. Walker and M.A. Cappelli, "High Density Plasma Neutralization of a Hall Thruster," AIAA-2001-3352, 37th Joint Propulsion Conference, 2001.

4. Welle, R.P., et al., "One Kilowatt Hydrogen and Helium Arcjet Performance," The Aerospace Corporation, ATR-91 (8443)-2, April 1993.

5. Isakowitz, S.J., J.P. Haopkins, Jr, and J.B. Hopkins, *International Reference Guide to Space Launch Systems.* 3 ed. AIAA, Reston, CA, 1999.

6. Private Communication, Paul Apfel, Boeing Space Systems, 13 Oct. 2002.

7. J. R. Wertz and W. J. Larson, Eds. *Space Mission Analysis and Design,* 3rd Ed. Microcosm Press, El Segundo, CA, 1999, pp 145-149.

8. V. A. Chobotov, Ed. *Orbital Mechanics,* 2nd Ed., AIAA, Reston, VA, 1996, pp 94-132.

9. D. R. Lide, Ed., *Handbook of Chemistry and Physics,* 81st Ed., CRC Press, Boca Raton, FL, 2000, p 6-140.

10. J. R. Wertz and W. J. Larson, Eds., *Space Mission Analysis and Design,* 3rd Ed. Microcosm Press, El Segundo, CA, 1999, pp 422-428.

11. Hargus, W.A., Jr., et al., "Preliminary Performance Results of the High Performance Hall System SPT-140," AIAA-2000-3250, 27th Joint Propulsion Conference, 2000.

12. Welle, R.P., et al., "One Kilowatt Hydrogen and Helium Arcjet Performance," AIAA-91-2229, 27th Joint Propulsion Conference, 1991.

Figure List

Table List

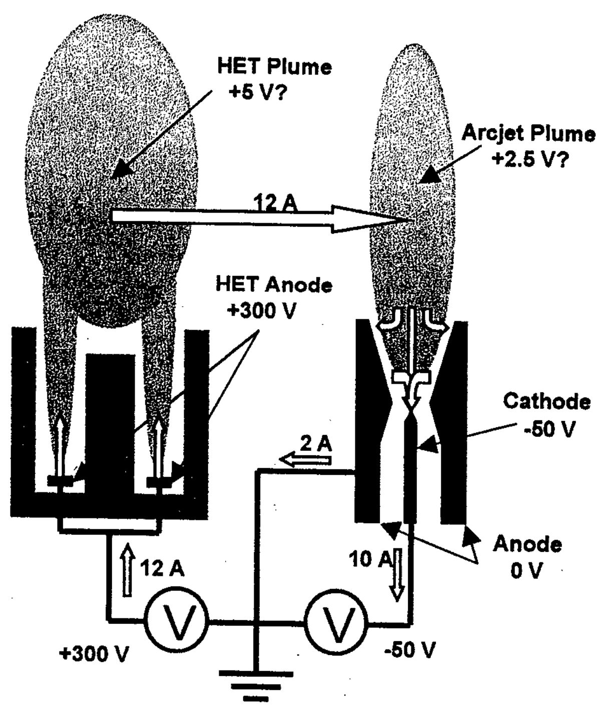
HET Plume
+5 V?
Arcjet Plume
+2.5 V?
12 A
HET Anode
+300 V
Cathode
-50 V
2 A
Anode
0 V
12 A
10 A
+300 V
-50 V

Fig. 1

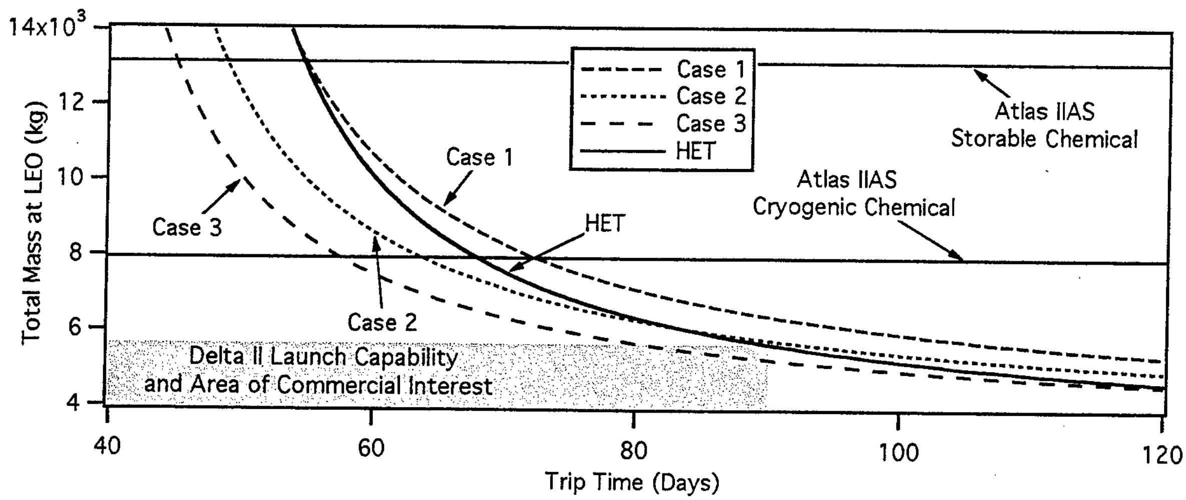

Fig. 2. Mass at LEO for helium arcjet-neutralizer (Cases 1-3) for various trip times.

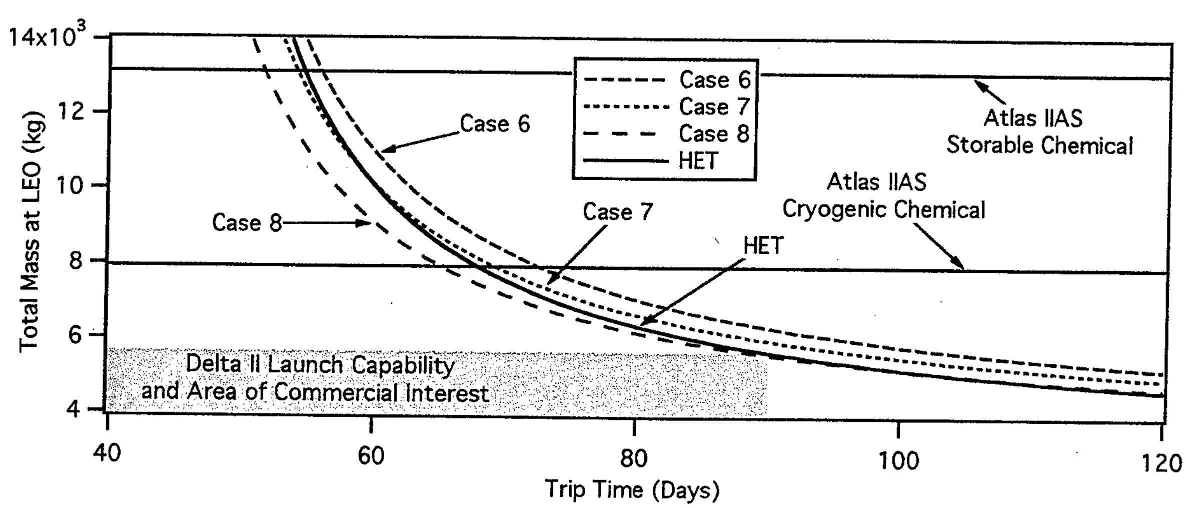

Fig. 3. Mass at LEO for hydrogen arcjet-neutralizer (Cases 6-8) for various trip times.

Table 1. Trade-offs between clustered and monolithic approach to high power electric propulsion.

Criteria	***100 kW class Monolithic***	***Clustered 10 kW***
Performance		
Efficiency	Higher	Lower
Specific Impulse (300V)	Same	Same
System Dry Mass	Lower	Higher
Reliability		
Thruster	About the Same	About the Same
PPU/PMA	Higher	Lower (more parts)
System Overall	Lower	Higher (redundancy)
Operational Flexibility		
Throttling	Lower	Higher
Orbit raise (Full power)	Same	Same
Station-keeping Suitability (Low power)	Lower	Higher
Suitability for Maneuvering/ Vectoring	Lower	Higher
Power Scalability	Lower	Higher
Developmental Cost	Very High	Low
Test Facility	Not Available/ Very High	Availability/ Very Low

Table 2. LEO to GEO model assumptions

Solar array specific mass	40 W/kg (radiation hardened)
Structural fraction	5%
Duty cycle	87.5% (mission averaged)
Tankage Fraction	
Xenon	10%
Helium	15% (cryogenic)
Hydrogen	20% (cryogenic)
ΔV	
Low thrust	5.2 km/s
Impulsive	4.3 km/s

Table 3. Nominal cluster of 4 SPT-140 Hall Thrusters

	HET Cluster w/ Cathodes	HET Cluster w/o Cathodes
Power (kW)	18	
Thrust (N)	1.160	
Isp (s)	1770	1947
Efficiency	56%	62%
Flow (mg/s)	66.8	60.7
Discharge V (V)	300	
Discharge I (A)	60	
Dry Mass (kg)	96.4	95.4
Thrust:Mass (N/kg)	0.0120	
Thrust:Power (N/kW)	0.0644	

Table 4. Cases1, 2, & 3: Hybrid HET cluster using various helium arcjet-neutralizers.

	Nominal Arcjet		Improved Perfromance Arcjet		Ideal Performance Arcjet	
	Arcjet-Neutralizer	Hybrid System	Arcjet-Neutralizer	Hybrid System	Arcjet-Neutralizer	Hybrid System
Power (kW)	2.5	20.5	5.75	23.75	10	28
Thrust (N)	0.375	1.535	0.780	1.940	1.190	2.350
Isp (s)	598	1256 (-29%)	900	1325 (-25%)	1200	1481 (-16%)
Efficiency	44%	46%	60%	53%	70%	61%
Flow (mg/s)	63.9	124.6	88.5	149.2	101.0	161.7
Discharge (V)	50		115		200	
Discharge (I)	50		50		50	
Dry Mass (kg)	9.1	104.5	21.0	116.4	36.4	131.8
Thrust:Mass (N/kg)	0.0412	0.0147 (+22%)	0.0371	0.0167 (+39%)	0.0327	0.0178 (+48%)
Thrust:Power (N/kW)	0.150	0.0748 (+16%)	0.136	0.0817 (+27%)	0.119	0.0839 (+30%)

Table 5: Case 4: Xenon arcjet neutralizer

	Xenon Arcjet-Neutralizer	Hybrid System
Power (kW)	5.75	23.75
Thrust (N)	4.460	5.620
Isp (s)	157	193 (-89%)
Efficiency	60%	22%
Flow (mg/s)	2896	2963
Discharge (V)	115	
Discharge (I)	50	
Dry Mass (kg)	21.0	116.4
Thrust:Mass (N/kg)	0.0327	0.0483 (+300%)
Thrust:Power (N/kW)	0.119	0.237 (+267%)

Table 6. Case 5: Hybrid argon HET cluster / arcjet-neutralizer.

	Ar HET Cluster w/ Cathodes	Arcjet-Neutralizer	Hybrid System
Power (kW)	18	8.625	26.625
Thrust (N)	0.93	3.7	4.630
Isp (s)	1947	285	344
Efficiency	62%	60%	29%
Flow (mg/s)	48.6	1323	1372
Discharge (V)	165	115	
Discharge (I)	90	75	
Dry Mass (kg)	95.4	31.4	126.8

Table 7: Case 6, 7, & 8: Hybrid cluster using various hydrogen arcjet-neutralizers.

	Arcjet Scaled from 1 kW		Improved Performance Arcjet		Ideal Performance Arcjet	
	Arcjet-Neutralizer	Hybrid System	Arcjet-Neutralizer	Hybrid System	Arcjet-Neutralizer	Hybrid System
Power (kW)	6.75	24.75	12	30	18.75	36.75
Thrust (N)	0.850	1.740	0.920	2.080	1.400	2.560
Isp (s)	900	1402 (-21%)	1200	1526 (-14%)	1500	1674 (-5%)
Efficiency	38%	48%	45%	52%	55%	57%
Flow (mg/s)	66	126.5	78	138.9	95.2	155.9
Discharge (V)	135		240		375	
Discharge (I)	50		50		50	
Dry Mass (kg)	24.6	120	43.7	139.1	68.3	163.7
Thrust:Mass (N/kg)	0.0346	0.0145 (+21%)	0.0211	0.0150 (+25%)	0.0205	0.0156 (+30%)
Thrust:Power (N/kW)	0.126	0.0703 (+9%)	0.0767	0.0693 (+8%)	0.0747	0.0697 (+8%)